Reconfigurable optical filter

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A narrowband, widely tunable optical filter with a reconfigurable spectrum is proposed, and the critical component for the filter operation is demonstrated. The filter is based on a whispering gallery mode resonator made of domain engineered $LiNbO_3$ crystal. The main feature of the filter is tunability of the spacing between some of the optical modes of the resonator. The spacing is electro-optically manipulated at 7 GHz in the linear regime with approximately 21 MHz/V tuning rate. The filter operates at 1.55 µm wavelength, and is characterised with 10 MHz bandwidth, 5 dB fibre-to-fibre insertion loss and 20 ns tuning speed.

Introduction: Photonic filters based on optical resonators have been devised to address shortcomings of microwave filters in their bandwidth and tunability. The microwave signals in photonic systems are sidebands of an optical carrier. Thus photonic filters can be used at any microwave frequency, from 1 to 100 GHz, and higher, providing the same characteristics throughout the band.

Absolute tunability of optical resonator based photonic filters is characterised by the ratio of their free spectral range (FSR) and linear tunability range. Tuning the filters does not change the FSR but only shifts the comb of the optical modes, making it overlap with itself for each frequency shift proportional to the FSR. Hence, the filter can be tuned at any prescribed single frequency if the linear tunability exceeds the FSR. Filters possessing such properties have been demonstrated recently [1, 2].

Some photonic applications call for narrowband filters passing simultaneously both the carrier and sidebands. For example, this is important for generation of spectrally pure microwave signals in optoelectronic oscillators [3, 4], where beating of the optical sidebands and the carrier on a fast photodiode generates microwaves. Tunability of the microwave frequency of the oscillator requires control over the change of the frequency difference between the filter passbands. This property is lacking in existing tunable filters, in which the entire filter spectrum shifts as a whole as the tuning voltage is applied.

In this Letter we propose theoretically and demonstrate experimentally a critical component of a novel miniature filter with electro-optically reconfigurable spectrum. The filter is based on a whispering gallery mode (WGM) resonator fabricated from a commercially available lithium niobate wafer. We prepared the crystalline resonator with a special domain structure that results in controllable shift of the frequency of a single resonator mode or a group of modes with respect to the other modes as a DC bias voltage is applied across the resonator. This allows us to tune one resonance of the optical cavity while keeping the rest of the spectra stationary. The filter may be characterised along the same lines as a Fabry-Perot filter with a tunable FSR. We show theoretically that the proposed method has the potential for fabrication of resonant photonic filters with arbitrary passband spectrum. Our filter operates at 1.55 µm wavelength, though the wavelength of operation is limited only by the absorption loss of lithium niobate and can be anywhere from about 1.0 to 1.7 µm. The reproducible value of the finesse of the filter (F) exceeds $F = 300$, but in some experiments we have achieved $F = 1000$.

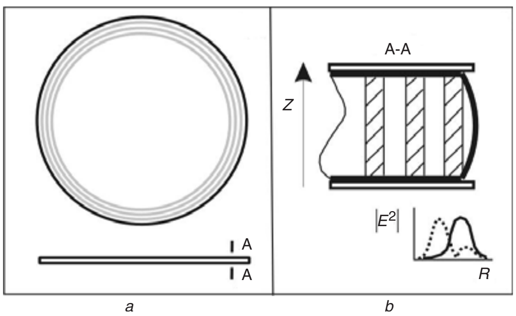

Fig. 1 *Schematic of metallised disc resonator used in reconfigurable filter; the resonator is made of periodically poled lithium niobate wafer*

a Picture of disc resonator. Inverted domain structure is shown by grey circles
b Cross-section of the resonator close to disc rim. Inverted domain structure is shown by striped areas. Two geometrical structures of electromagnetic modes of resonator (radius dependence of mode power distribution) are shown under resonator crossection. The mode depicted by solid line is barely shifted by applied voltage, whereas mode shown by dotted line moves

Theory: The filter is a circular resonator made from electro-optic material (Fig. 1*a*). It is possible to change the refractive index of the material by application of a DC electric field. A homogeneous change of the electric field results in a homogeneous change of the refractive index for a single-domain crystalline resonator and, as a consequence, in a frequency shift of the whole resonator spectrum. We propose to manipulate the domain structure to produce an inhomogeneous electro-optic effect in the resonator in such a way that radical mode families experience frequency shifts with opposite senses to other mode families.

The maximum frequency shift of the TE and TM mode can be found from

$$\Delta\nu_{TE} = \nu_0 \frac{n_e^2}{2} \frac{\left(\int_V r_{33}(\vec{R}) |\vec{E}_{TE}(\vec{R})|^2 E_Z d\vec{R} \right)}{\left(\int_V |\vec{E}_{TE}(\vec{R})|^2 d\vec{R} \right)}$$

$$\Delta\nu_{TM} = \nu_0 \frac{n_0^2}{2} \frac{\left(\int_V r_{13}(\vec{R}) |\vec{E}_{TM}(\vec{R})|^2 E_Z d\vec{R} \right)}{\left(\int_V |\vec{E}_{TM}(\vec{R})|^2 d\vec{R} \right)}$$

where $\nu_0 = 2 \times 10^{14}$ Hz is the carrier frequency of the laser; $r_{33}(\vec{R}) = \pm 31$ pm/V and $r_{13}(\vec{R}) = \pm 10$ pm/V are the electro-optic coefficients, the sign of which is determined by the direction of the domain of the crystal in point R, which could be either $+\vec{z}$ or $-\vec{z}$, with respect to the homogeneous DC bias electric field E_Z; $n_0 = 2.28$ and $n_e = 2.2$ are the refractive indices of $LiNbO_3$; and $\vec{E}_{TE}$ and $\vec{E}_{TM}$ are the amplitudes of the electric fields of the modes. The integration is taken over the resonator volume V.

Various modes of a WGM resonator have various spatial dependences (Fig. 1*b*). Choosing spatial dependence of the electro-optic coefficients in a correct manner by poling the crystal we are able to change tunability of the modes in different ways.

Apparatus: A schematic diagram of the filter configuration is shown in Fig. 1. Several 2.6 mm diameter disc-shaped resonators of $LiNbO_3$ were fabricated, with 120 µm thickness. The rims of the cylindrical discs were polished to resemble the surface of a sphere.

A ferroelectric domain structure reminiscent of a set of rings concentric with the axis of the disc resonator was created in house. This was done by dragging a 1 µm diameter electrode across the surface of the crystal while applying a 2.5 kV bias between the electrode and the bottom of the crystal, causing a permanent change in the structure of the material polarisation. The poling process took place at room temperature and was visualised in situ by reflecting light from the bottom surface of the crystal. Domain walls, that is, barriers between polarisations parallel to $+\vec{z}$ and $-\vec{z}$ directions, are clearly visualised as dark bands in the reflected light.

The top and bottom surfaces of the polished and poled disc resonator were placed into contact with metal electrodes. These electrodes were connected to a 0–150 V regulated DC power supply. A probe beam of 1.55 µm scanned over 20 GHz was coupled into the resonator through a diamond prism. This allowed us to observe the absorption spectrum of the poled disc resonator and the motion of the modes as the voltage bias across the resonator axis was increased.

Results and analysis: The first disc was poled with a ring-shaped domain pattern 5 µm edge-to-edge at the disc rim and a 35 µm-thick ring-shaped domain 20 µm away. The probe was coupled into the WGMs of the resonator with a quality factor of 10^7.

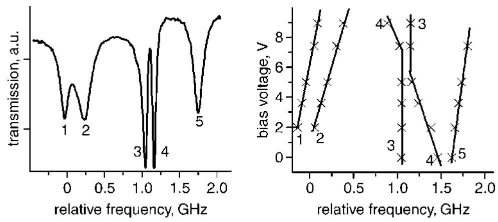

Fig. 2 *Spectrum of WGM resonator (left-hand side) and its tunability (right-hand side)*

Resonances 3 and 4 move through each other with bias voltage change. When frequencies of modes coincide, modes interact due to residual light scattering in disc resonator

When the probe beam was coupled into the high-Q modes of the first disc and voltage was applied, the radical mode was observed to change frequency with respect to the rest of the spectra at a rate of 21 MHz/V (Fig. 2). The Q-factor of the resonance was maintained constant through the most of the motion. The mode motion was observed over 10 V of bias change (Fig. 3).

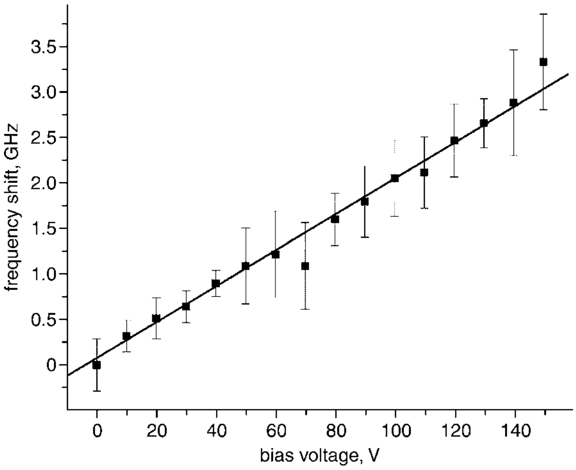

Fig. 3 *Relative frequency shift between modes 3 and 4 (Fig. 2) against applied bias voltage*

We used a single prism coupler in our experiment. Such a coupler allows us to observe the mode motion in the resonator; however, it is unsuitable for demonstrating a passband optical filter that requires two-prism coupler [2], so further studies are required.

Conclusions: We have demonstrated a critical component of a tunable microwave optical domain filter with reconfigurable spectrum. The filter can be used in various photonic applications where passing both the optical carrier and optical sidebands is important, e.g. for high-density telecommunication networks, as well as in microwave photonics communication systems.

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References

1 Sadot, D., and Boimovich, E.: 'Tunable optical filters for dense WDM networks', *IEEE Commun. Mag.*, 1998, **36**, pp. 50–55
2 Savchenkov, A.A., Ilchenko, V.S., Matsko, A.B., and Maleki, L.: 'Tunable filter based on whispering gallery mode', *Electron. Lett.*, 2003, **39**, pp. 389–391
3 Yao, X.S., and Maleki, L.: 'Optoelectronic microwave oscillator', *J. Opt. Soc. Am. B*, 1996, **13**, pp. 1725–1735
4 Strekalov, D., Aveline, D., Yu, N., Thompson, R., Matsko, A.B., and Maleki, L.: 'Stabilizing an optoelectronic microwave oscillator with photonic filters', *J. Lightwave Technol.*, 2003, **21**, pp. 3052–3061